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REVIEW ARTICLE

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Indoor photovoltaics, *The Next Big Trend* in solution-processed solar cells

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Abstract

Indoor photovoltaics (IPVs) have attracted considerable interest for their potential to power small and portable electronics and photonic devices. The recent advancemes in circuit design and device optimizations has led to the power required to operate electronics for the internet of things (IoT), such as distributed sensors, remote actuators, and communication devices, being remarkably reduced. Therefore, various types of sensors and a large number of nodes can be wireless or even batteryless powered by IPVs. In this review, we provide a comprehensive overview of the recent developments in IPVs. We primarily focus on third-generation solution-processed solar cell technologies, which include organic solar cells, dye-sensitized solar cells, perovskite solar cells, and newly developed colloidal quantum dot indoor solar cells. Besides, the device design principles are also discussed in relation to the unique characteristics of indoor lighting conditions. Challenges and prospects for the development of IPV are also summarized, which, hopefully, can lead to a better understanding of future IPV design as well as performance enhancement.

KEYWORDS

dye-sensitized solar cells, indoor photovoltaics, organic solar cells, perovskite solar cells, quantum dot solar cells

1 | INTRODUCTION

Energy is considered as one of the primary challenges for the sustainable development of human societies. Environmentally friendly renewable energy sources, as an alternative to conventional fossil fuels, have witnessed extensive development during past decades because of their potential to provide energy without greenhouse gas emissions and hence mitigate climate change through global warming. Among a variety of renewable energy sources, photovoltaic (PV) technologies which enable direct conversion of solar energy to electricity account for a substantial and growing proportion of alternative energy electricity generation capacity globally. It is also attractive as it is a modular technology which in principle can be installed everywhere without geographical limitation.[1] Solution-processed PV cells form a subset and have the benefit of low cost, due to the low energy budget incurred in their fabrication. They are therefore particularly suited for PV conversion in environments which have significantly lower light intensity than that available from direct sunlight. The efficiency of energy conversion in low light environments (typically 0.01 Sun) can in fact be higher in solution-processed organic PV cells

compared to their inorganic counterparts which operate in direct sunlight. This class of PV has attracted considerable attention not only in terms of photovoltaic device optimization but also in materials and chemistry innovations.[2-4]

Because of the recent advances in circuit design and device optimizations, the power required to operate electronics for the internet of things (IoT), such as distributed sensors, remote actuators, and communication devices, has been significantly reduced. As presented in Figure 1 (A), the cost of low-power electronics has also reduced due to increasing integration and use of low-cost substrates together with low-cost manufacturing routes such as printing. To further enhance the versatility of location and applicability, deploying PV technologies into the indoor environment to realize wireless and battery-free self-powered electronic systems such as wireless sensors, radio-frequency identification (RFID) tags, and Bluetooth beacons becomes an attractive option.[5] A significant portion of these electronic systems will form a crucial part of the IoT ecosystem, where large networks of connected devices collect and communicate data from the environment. Having long-term local energy sources for providing power to devices in such networks can be partly realized through photovoltaic conversion and capacitive storage. However, the prevalent silicon (Si) PVs generally have poor performance under ambient light conditions, are also costly when operated at much lower levels of energy conversion than the capability of Si (which is not even approached under terrestrial solar insolation) and difficult to integrate into small, lightweight, and portable systems for the IoT.[5-7]

As alternatives to Si-based PVs, the third-generation solution-processed solar cells, including dye-sensitized solar cells (DSSCs), organic solar cells (OSCs), quantum dot solar cells (QDSCs), and perovskite solar cells (PSCs), which have made considerable progress in recent years, are a viable option. Due to their large absorption cross-section, substrate-independent processability and broad bandgap customizability, there has been extensive research on deploying these solar cells into indoor photovoltaic (IPV) applications which can be used for powering IoT-related electronics.[8] However, it is worthwhile emphasizing that different types of third-generation PVs exhibit different drawbacks, such as poor stability, toxicity in PSCs, and photodegradation in OSCs.[9]

In this review, we first introduce the design principles for IPV since the operating conditions and power output are considerably different from solar cells designed to operate under AM1.5 (1 kW m^{-2}) insolation. Then, we summarize the recent development of IPVs from first-generation Si-based PVs to third-generation counterparts by tracking performance improvement as well as the underlying physical mechanisms. According to the property of each IPV, discussions about potential challenges that hinder their indoor application and potential solutions are presented.

2 | THE DESIGN PRINCIPLES FOR IPVs

The device working area for an IPV is only a few square centimeters, with incident light intensity as low as 0.1–10 W m^{-2} mainly in the visible region from diffuse solar radiation in the indoor environment and ambient

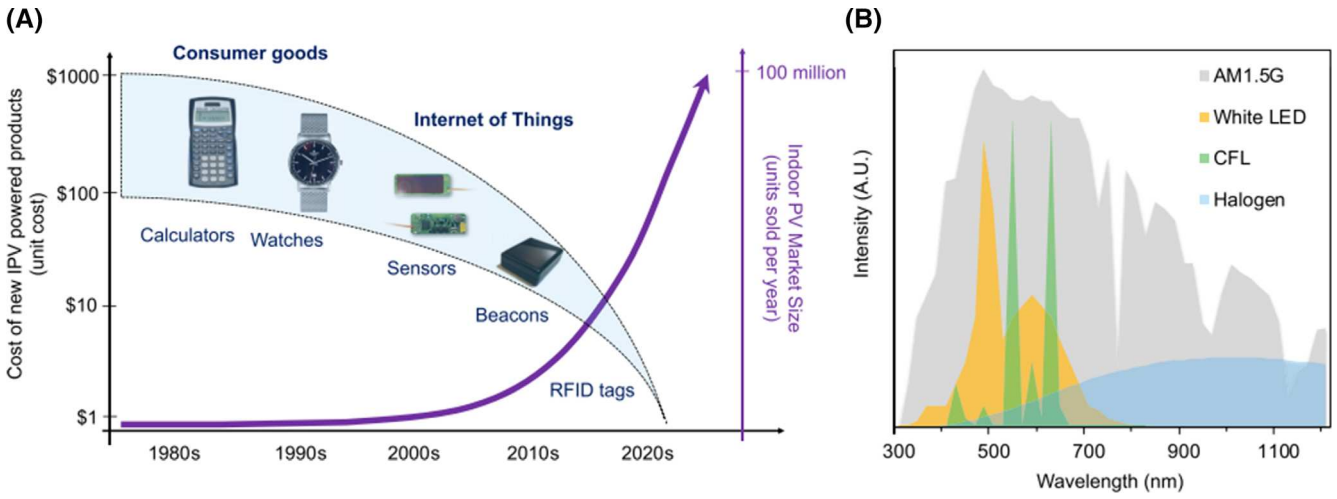

FIGURE 1 (A) An overview of the cost of indoor photovoltaic (IPV)-powered devices and the prediction of IPV market size. (B) Different light spectra under which IPV efficiency is evaluated, including the standard solar spectrum AM1.5G and typical spectra from white light-emitting diode (LED), compact fluorescent lamps (CFL), and Halogen sources. Copyright 2019, Elsevier

artificial light sources such as incandescent light bulbs, compact fluorescent lamps, and white light-emitting diodes (LEDs).[10] Indoor lighting applications are designed and optimized based on the spectral sensitivity of human eyes, which peaks at 550 nm in a range from 380 to 780 nm.[11] Therefore, IPVs can exploit the advantage of a higher open-circuit voltage (V_{oc}) when shifting to larger bandgaps, while simultaneously benefiting from a high photon yield. For indoor lighting, lux is used as a metric of light intensity, corresponding to the spectrum responsivity of human eyes to a different wavelength. Typically, 200 lux is for living room environments and 300–2000 lux for the office or other indoor environments.[12,13]

Changing the light source from AM 1.5G to indoor lights changes not only the intensity but also the spectrum of the incident lighting as indoor light lies only in the visible range, as shown in Figure 1(B). Therefore, optimization of IPV is sought with photoactive materials having wider bandgaps than Si. The extinction coefficient of active materials is also of great importance. Other issues include the optimization of the interfacial layers, which accounts for the charge transfer and collection.[8]

3 | THE DEVELOPMENT OF PHOTOVOLTAICS FOR INDOOR APPLICATION

3.1 | Conventional thin-film Si-based solar cells for indoor application

To date, Si-based solar cells have occupied most of the market for outdoor PV applications due to their mature manufacturing technologies. According to the crystalline phase, Si-based solar cells can be classified into mono-crystalline (*mc*-), poly-crystalline (*pc*-), and amorphous (*a*-) types, in which amorphous Si-based solar cells have gained considerable attention in indoor applications owing to their cost-effective manufacture from gaseous plasma sources in thin-film form. This enables them to be formed on low-cost flexible substrates and draws on the wealth of research and development spanning four decades on improving stability and lifetime. With a bandgap of 2 eV, it is suitable for IPV application and was the first technology incorporated into low-power indoor electronics (the solar/light-powered calculator perhaps being the most ubiquitous one).[9] In the early stage, research of Si-based IPVs was limited to comparing commercial solar cells under low-illumination testing environments and the lack of appropriate models.[14] In 2009, Turkenburg et al. measured 41 industrial mono- and multi-crystalline Si-based cells between 0.01 and 1000 W m^{-2}, and they then evaluated the accuracy of modeling based on one-diode and two-diode models.[15] Later, the fill factor (FF) expression was used by the same research group to model irradiance intensity dependence on the efficiency of Si-based IPVs, and reported calculations of PV power output based on spectrally resolved irradiance.[16] They pointed out that hydrogenated amorphous silicon (*a*-Si:H) cells exhibited only around 8% efficiency under Standard Testing Conditions (STC), for solar cells while up to 20% under energy-efficient lighting environments. Even though *c*-Si cells showed larger efficiency under STC, only 3%–6% efficiency can be obtained under energy-efficient LED light, as shown in Table 1. The higher efficiency in *a*-Si:H is attributed to a relatively higher V_{oc} under low light associated with the relatively larger bandgap of *a*-Si:H compared to *mc*-Si. Indeed, the calculated efficiency of *a*-Si:H solar cells is around 17.68% under LED light irradiance and the real device efficiency can reach 15.2% under the irradiance of 1.1 mW cm^{-2} LED light.[17]

In addition to incident-dependence studies on Si-based IPVs, some strategies have been demonstrated to improve the photovoltaic performance of Si-based IPVs. For example, a small area *mc*-Si cell was fabricated for low-flux light harvesting in the near-infrared transparency range.[18] The maximum power conversion efficiency (PCE) of 17.12% and 80% external quantum efficiency (EQE) was achieved when the cell was examined under low-flux 850 nm LED illumination by inclusion a low-pressure chemical vapor deposition (LPCVD) Si_3N_4 passivation layer (Figure 2(A,B)) in the cells. Although an intensity-dependent reduction of V_{oc} suppresses the PCE under low-flux conditions, LPCVD Si_3N_4 passivation enables a shunt resistance above 10 MΩ cm^{-2} (Figure 2(C,D)) and thus alleviates the degradation of PCE and EQE.

Apart from the investigation on rigid Si-based IPVs, great attention has also been paid to flexible, disposable, and potentially wearable Si-based IPVs for powering next-generation electronic systems.[19-21] Figure 2(E) depicts a flexible *a*-Si:H solar cell with a Al/Ag/*a*-Si:H (n)/*a*-Si:H(i)/*a*-Si:H(p)/indium zinc oxide configuration.[3] The cell provides an efficiency of 3.4% compared to a similar structure on the glass. However, there is no data on the current density-voltage (*J*-*V*) characteristics under indoor lighting conditions. Nevertheless, the cells show the potential of *a*-Si:H for low cost, large-scale production using roll-to-roll processes on flexible substrates for providing PV power in applications such as smart labels, food sensing electronics and RFID.

3.2 | DSSCs for indoor application

As one of third-generation PV devices, DSSCs are sensitive to the variation of irradiance and hence can be

TABLE 1 Silicon solar cells characteristics under STC and indoor white-LED lighting. Copyright 2009, Elsevier

	J_{sc} (μA and mA cm^{-2})			V_{oc} (V)			FF (%)			Efficiency (%)	
	LED1 μA	LED2 μA	STC mA	LED1	LED2	STC	LED1	LED2	STC	LED1/2	STC
a-Si:H	118	113	13.5	0.67	0.67	0.82	0.68	0.68	0.7	∼19–21	7.7
mc-Si	138	94	∼37	0.4	0.4	∼0.7	0.35	0.35	∼0.8	5.3–5.6	18.2
pc-Si	119	86	∼35	0.3	0.3	∼0.6	0.35	0.35	∼0.8	3.6–3.7	16.8

Abbreviations: FF, fill factor; LED, light-emitting diode; STC, Standard Testing Conditions.

applied for light energy harvesting both indoors and outdoors.[8,9] The operation of DSSCs is similar to photosynthesis which occurs inside plants, with photo-sensitization of dye on the working electrode, typically TiO_2, generating electrons before being replenished by an electrolyte through a redox reaction.[22] Since Grätzel first reported DSSCs with PCE over 7%, enormous progress has been made in both outdoor and indoor DSSCs, including synthesis of novel dyes, optimization of collecting material, and development of electrolytes.[7,23]

Among the components in indoor DSSCs, the application of novel dyes play a significant role in effective light harvesting.[7] Porphyrin is one type of commonly used dye sensitizer, with a high extinction coefficient, excellent stability, low synthesis cost, and efficient electron transferability.[24,25] For example, Liu et al. synthesized a new push-pull porphyrin dye Y1A1 (structure in Figure 3(A)) for indoor DSSCs. Resultant cells showed not only superior performance with optimal PCE of 9.22% under AM1.5 G but also exhibited excellent charateristics with a V_{oc} of 0.5 V and PCE of 13.5%–19.5% under ambient lighting illumination of 300–2400 lux (Figure 3(B–D)).[27]

Additionally, anthracene-based molecules have been used in indoor DSSCs because of their unique photophysical properties such as bright blue electroluminescence.[28,29] A group of metal-free anthracene-based dye molecules with donor-acceptor-π-acceptor (D-A-π-A) configuration were synthesized by Tingare et al., and they proved that sensitizer TY6 can display outstanding PCE of 20.72% and 28.56% under 6000 lux of LED and T5 fluorescent light source,[26] respectively, which is because of the spectral match of LED light and energy level alignment with TiO_2 for efficient electron injection.[30] Figure 4(A–C) are optical and electrical characteristics of anthracene-based dye TY3, TY4, and TY6 molecules in DSSCs, respectively. Other anthracene-based sensitizers were also studied, wherein AN3-based DSSCs achieved a PCE of 5.45% at 1000 lux and dye AN11-based DSSC obtained a PCE of 11.26% with a large area of 26.80 cm^2.[31,32]

The aforementioned improvement of indoor DSSCs not only relies on sensitizers but also other critical factors such as the selection of charge carrier blocking layers, replacement of liquid electrolytes with solid electrolytes, and device architecture innovations. Liu et al. investigated the effect of different TiO_2 as a blocking layer on DSSCs performance. They found the sprayed compact TiO_2 enable DSSCs to obtain outstanding PCE efficiencies of 15.26% and 15.12% under low light intensities of 1001 and 250 lux, much higher than 8.56% and 6.19% in the reference cells.[33] Moreover, replacing the conventional liquid electrolyte with solid-state electrolyte facilitates the improvement in performance of indoor DSSCs. As reported recently, PCE of 15.39% and 20.63% were achieved with quasi-solid-state electrolyte under low light intensities of 200 and 600 lux, respectively.[34] It is worth mentioning that the optimization of device architecture is also a reliable method for obtaining better performance in indoor DSSCs. As shown in Figure 4(D–F), an advanced DSSC configuration was reported by Cao and coworkers, and a significantly high PCE of 31.8% under 1000 lux light intensity was realized using Y123/XY1b as cosensitizer.[35]

3.3 | OSCs for indoor application

Since the first report of OSCs, significant progress has been made during the past two decades, with PCE steadily improving from less than 4% to over 15% under AM1.5 illumination.[36-39] It was demonstrated by Freunek et al. that the optimum bandgap for harvesting indoor light is 1.9 eV instead of 1.4 eV for standard sunlight.[40] Therefore, unlike *mc*-Si cells, the donor/acceptor materials as an active layer inside OSCs usually have a better spectral match with indoor light, which can generate higher PCE in IPV applications. For example, Cutting and coworkers compared *mc*-Si, *a*-Si and copper indium gallium selenide (CIGS) with some selected OSCs.[41] They found three types of OSCs (Figure 5(A)) showed remarkable PCEs under the white LED illumination, reaching 6.89%, 12.83%, and 21.04% for P3HT:PC_{60}BM: nanoparticles, P3HT: PC_{60}BM and PCE10: PC_{70}BM cells, respectively. Besides, a better indoor performing OSC was obtained by using 1′,1″,4′,4″-tetrahydro-di[1,4]methanonaphthaleno[5,6]fullerene-C_{60} (ICBA) and

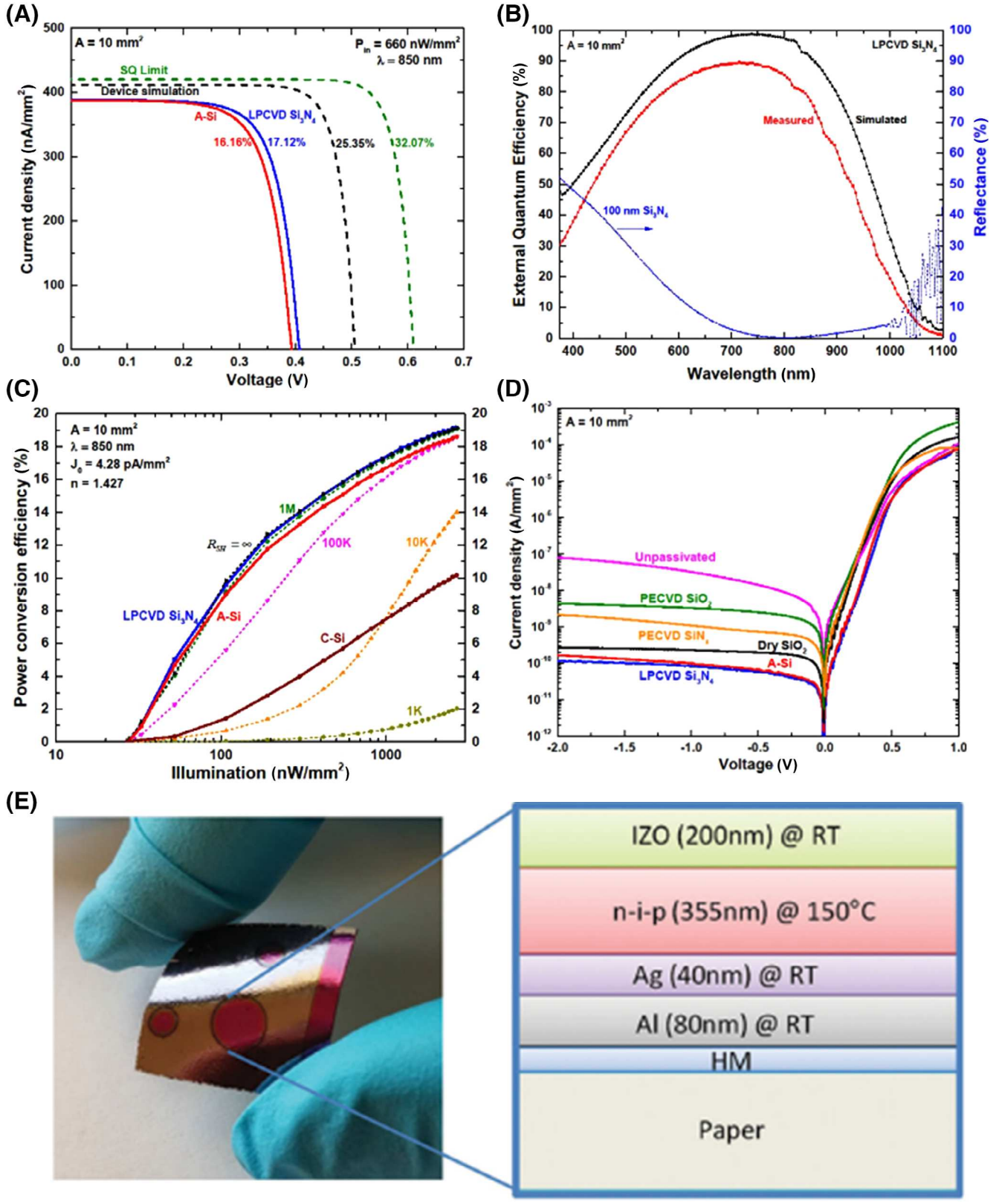

FIGURE 2 (A) *J-V* characteristics with the Shockley–Queisser (SQ) limit. (B) Measured and simulated external quantum efficiency (EQE) for cells with 100 nm LPCVD Si_3N_4 passivation layer. (C) Measured power conversion efficiency (PCE) dependence of near-infrared (NIR) illumination for different passivation methods. Copyright 2017, IEEE. (D) *J-V* under a dark condition with different passivation methods. (E) Image of a flexible *a*-Si:H solar cell on a paper substrate, with a schematic illustration of device configuration. Copyright 2015, Wiley-VCH

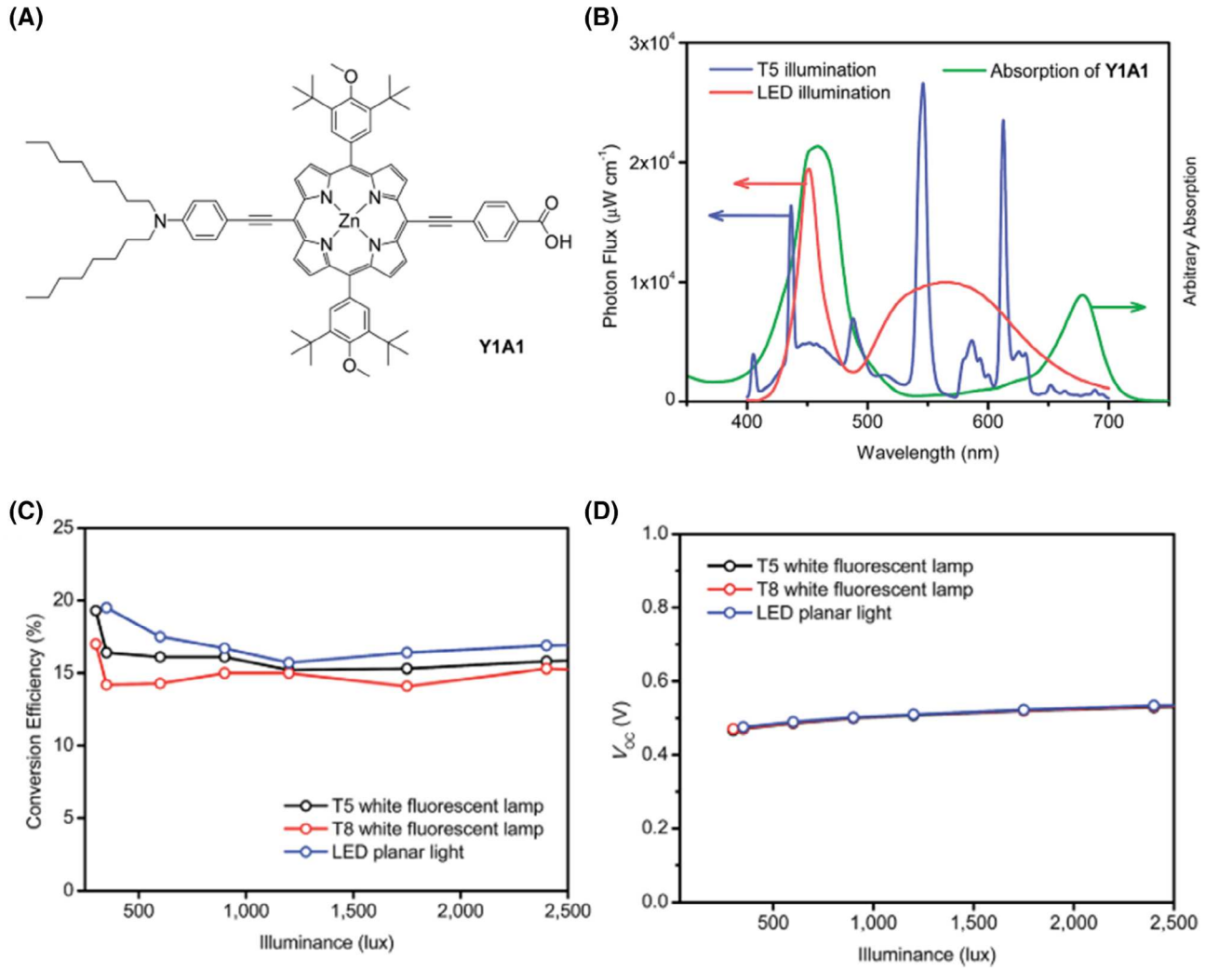

FIGURE 3 (A) Molecular structure of the porphyrin dye Y1A1. (B) Absorption spectra overlap of Y1A1 with solar irradiance, T5 illumination[26] and light-emitting diode (LED) illumination, respectively. (C, D) Power conversion efficiency (PCE) and V_{oc} dependence as a function of illuminance. Copyright 2016, the Royal Society of Chemistry

doping Ni into the ITO layer.[42] The device structure and energy band diagram are shown in Figure 5(B,C). It should be pointed out that for indoor application, a high shunt resistance is crucial; however, the series resistance is not equally essential to keep a low value, in contrast to standard solar cell applications.[9,43]

On the other hand, there is no guarantee that PCE under one sun will indicate the same characteristics under an indoor light environment, and this is closely related to the selectivity of photosensitive polymers. Lee et al. suggest that PCDTBT: $PC_{71}BM$ OSCs outperform the PTB7: $PC_{71}BM$ counterparts under 300 lux, generating P_{max} of 13.9 μW cm^{-2} with PCE of 16.6%, though PTB7: $PC_{71}BM$ displayed a higher PCE under one sun, as shown in Figure 5(D–F).[12] The high performance of PCDTBT: $PC_{71}BM$ devices under low-flux paves a way to compete with other IPVs such as *a*-Si:H IPVs that give high efficiency under low illumination. Furthermore, a replacement of traditional fullerene-based electron-acceptor materials with nonfullerene acceptors can yield even higher indoor performance of OSCs due to greater thermal stability, photochemical stability, and longer device lifetimes induced by novel nonfullerene materials.[44-46] In recent work by Cui et al., blending of a nonfullerene acceptor IO-4Cl and PBDB-TF polymer donor enables a 1 cm^2 OSC to obtain a PCE of 26.1%, and V_{oc} of 1.10 V under 1000 lux LED, as well as 1000 h of continuous operation under indoor light conditions.[47] As shown in Figure 6(A), light-intensity data yield a slope close to unity, which infers that the ratio of photons to electrons remains constant with decreasing light intensity. Under these three illumination conditions, PCEs ranged from 22.2% to 26.1%, attributed to high current and significantly high V_{oc} values. When it comes

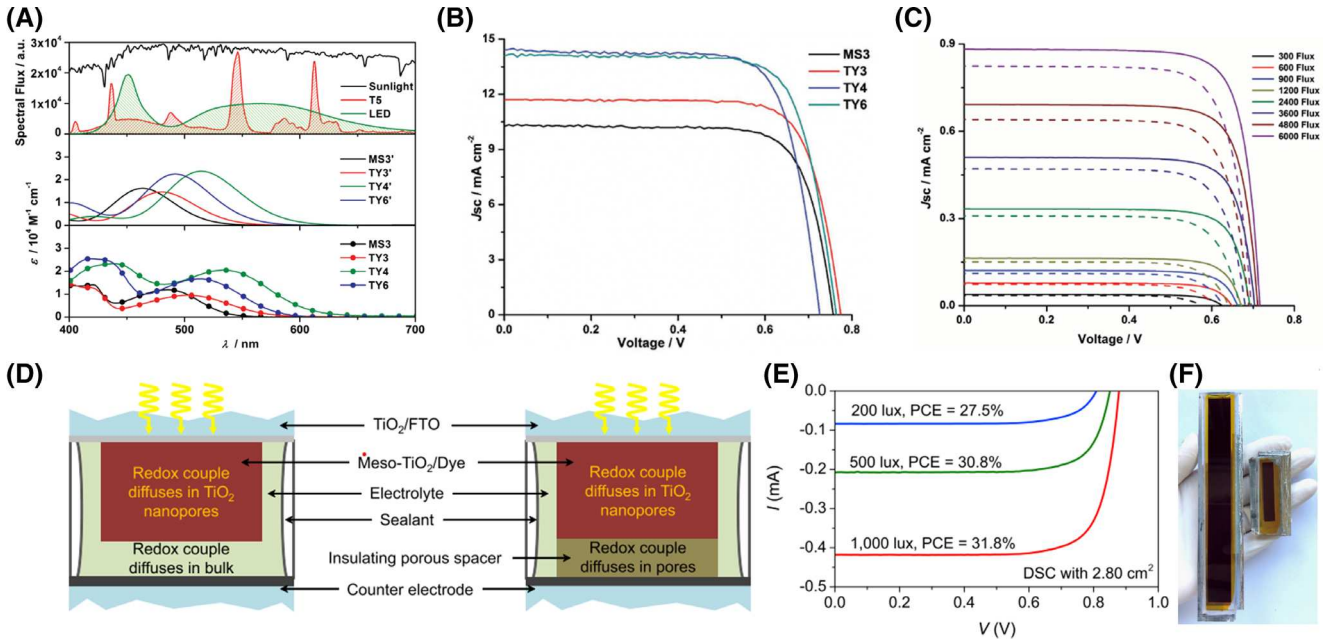

FIGURE 4 (A) The irradiance and emitting spectra of sunlight, T5, and light-emitting diode (LED) lights, with calculated and measured absorption spectra of MS3, TY3, TY4, and TY6 dyes solution. (B) *J-V* characteristics for DSSCs with MS3, TY3, TY4, and TY6 under AM 1.5G illumination. (C) *J-V* characteristics for TY6 DSSCs with (solid line) and without (dashed line) coadsorbent CDCA at different T5 light luminance. Copyright 2017, Wiley-VCH. (D) Schematic of novel DSSC architecture using p-type hole charge collector in direct contact with TiO_2 scaffold. (E) *J-V* curves of the DSSC of 2.80 cm^2 size under varying intensities of the indoor light. (F) Picture of two DSSCs with photoactive areas of 2.80 and 20.25 cm^2. Copyright 2018, Elsevier

to large-area cells, a 23% PCEs under indoor illumination at 200 lux was achieved for a 4 cm^2 blade-coated cell. Interestingly, over 40% PCE is predicted through simulation (Figure 6(B,C)). This indicates a promising potential of OSCs for powering a wide range of indoor electronics. Meanwhile, a large-area module >20 cm^2 with a PCE of 10.4% using a nonfullerene blend was demonstrated by Liao and coworkers, reaching PCE of 21.8% under a fluorescent lamp of 1000 lux (Figure 6(D)).[48]

3.4 | Colloidal QDSCs for indoor application

Colloidal quantum dots are a type of nanoscale semiconductor crystals that exhibit unique optical, electrical properties, including size-dependent light absorption, excellent stability, high charge mobility, and facile synthesis.[11,49-56] Till now, PCE of QDSCs has been improved up to 13%.[13,49,57-64] However, despite many efforts being made in QDSCs, to the best of our knowledge, reports on indoor QDSCs are still lacking within the solar cell community. However, some hybrid QD-organic and QD-metal chalcogenide cells have been explored for indoor applications.

Otsuka et al. introduced Si QDs into PTB7 and PTB7-Th polymer system by mixing QDs and polymers at certain weight ratio and fabricated Si QD-based hybrid PVs generate a PCE of 3.0% and 9.7% under one sun and LED light irradiance, respectively.[65] Figure 7(A,B) depicts the energy diagram and *J-V* curve of the reported cells. However, it is noticeable that this PCE value is not comparable to the aforementioned Si-based PVs, DSSCs, and OSCs for indoor application, which may be resulting from undesirable charge transfer between QDs and polymers, such as high recombination rate and lack of proper QD surface functionalization.[57] In contrast, solution-processed metal chalcogenides QDSCs have shown the possibility of achieving promising IPV behavior.[13]

Very recently, Hou el at. reported colloidal metal chalcogenide-based QDSCs with a 19.5% record efficiency under 2000 lux indoor light condition and 11.6% under 1.5 Sun concentrated solar irradiance (Figure 7(C)).[13] They also demonstrated that an extremely high exciton density could be realized by multiphoton absorption together with judicious surface ligand engineering, which lays the foundations for high-performance QDSC for IPV developments.[13] Notably, a remarkable amount of power can be efficiently generated under various light illumination conditions, compensating for irradiance differences due to latitude and time zone variations

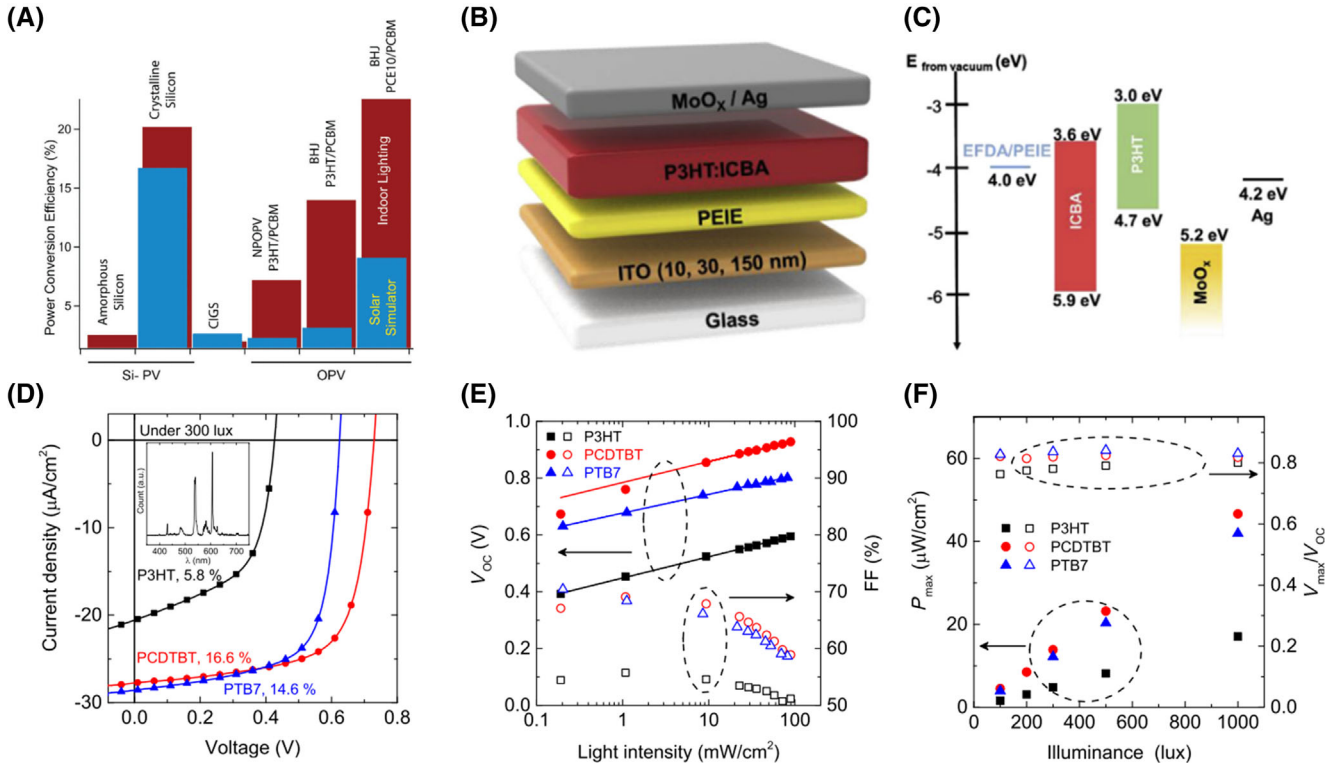

FIGURE 5 (A) Power conversion efficiency (PCE) comparison of *c*-Si, *a*-Si, CIGS, and organic solar cells (OSCs) under AM 1.5G solar simulator illumination (blue) and under light-emitting diode (LED) illumination (red). Copyright 2016, the Royal Society of Chemistry. (B) Device configuration of P3HT: ICBA inverted OSCs. (C) Energy bandgap schematics of studied OSCs. Copyright 2019, Elsevier. (D) *J-V* curves of P3HT:PCBM, PCDTBT:$PC_{71}BM$, and PTB7:$PC_{71}BM$ devices under 300 lx fluorescent lamps. The spectrum of 300 lx fluorescent lamps is present in the inset. (E) V_{oc} (solid symbols) and fill factor (FF) (open symbols) of the three OSCs at a different light intensity of AM1.5 G. (F) Maximum power output density, P_{max}, (solid symbols) and V_{max} to V_{oc} ratio (open symbols) of OSCs at different illumination levels of fluorescent lamps. Copyright 2016, the American Institute of Physics

(Figure 7(D)). Moreover, a linear increase in the short-circuit current (J_{sc}) and a semi-logarithmic increase in the V_{oc} with increasing light intensity from 0.01 to 1000 mW cm^{-2} can be observed, as shown in Figure 7(E).

3.5 | PSCs for indoor application

Beyond the IPV systems described above, metal halide PSCs have also emerged as a promising alternative for indoor application.[66-70] Chen et al. conducted the first investigation on indoor PSC in 2015, wherein they precisely controlled traps in the perovskite active layer and carrier dynamics via designing electron transfer layer (ETL) and thus successively made a PSC with 27.4% PCE under indoor environment.[71] Notably, as presented in Figure 8(A), there is only negligible hysteresis behavior in the *J-V* curves, indicating an incident-light-dependent hysteresis characteristic that is more likely to occur under one sun but not low light intensity conditions. Besides, a large-area device of 5.44 cm^2 also exhibited a high PCE of 20.4% and promising long-term stability. Optimization of the ETL was shown to be an effective method to further improve PSC performance under indoor light. A mesoporous TiO_2 layer was incorporated into PSCs by atomic layer deposition (ALD), spray pyrolysis (SP), and the sol–gel (SG) by Di Giacomo et al.[72] Among these, PSCs with ALD TiO_2 layer was found to be superior in terms of J_{sc}, V_{oc}, dark current, FF and PCE, with PCE reaching 24% under 200 lux compared to 14.3% and 9.3% for the other two equivalents. The cross-sectional scanning electron microscopy in Figure 8(B) illustrates a clear planar structure inside the best PSCs. Also, Dagar et al. reported a $CH_3NH_3PbI_3$-based planar PSC incorporating solution-processed SnO_2/MgO composite ETL, which achieved a 25% PCE under 200 lux indoor illumination.[73] It was seen that the MgO layer plays an essential role since MgO can largely suppress hysteresis under both 200 and 400 lux illumination (Figure 8(C,D)). Perovskite compound is generally represented as ABC_3 where A site can be Methylammonium (MA), formamidinium (FA), cesium (Cs) single cations, or MA-FA-Cs triple cations and where B site can be occupied by Pb and C are usually halide or mixture of halide ions.[74,75] The adjusting stoichiometric ratio of halide ions or using triple cations may bring about the possibility of better PSC performance as a result of a closer bandgap to 1.9 eV. Accordingly, Br^- ions were added into the PSCs to increase their bandgap values by Wu et al.

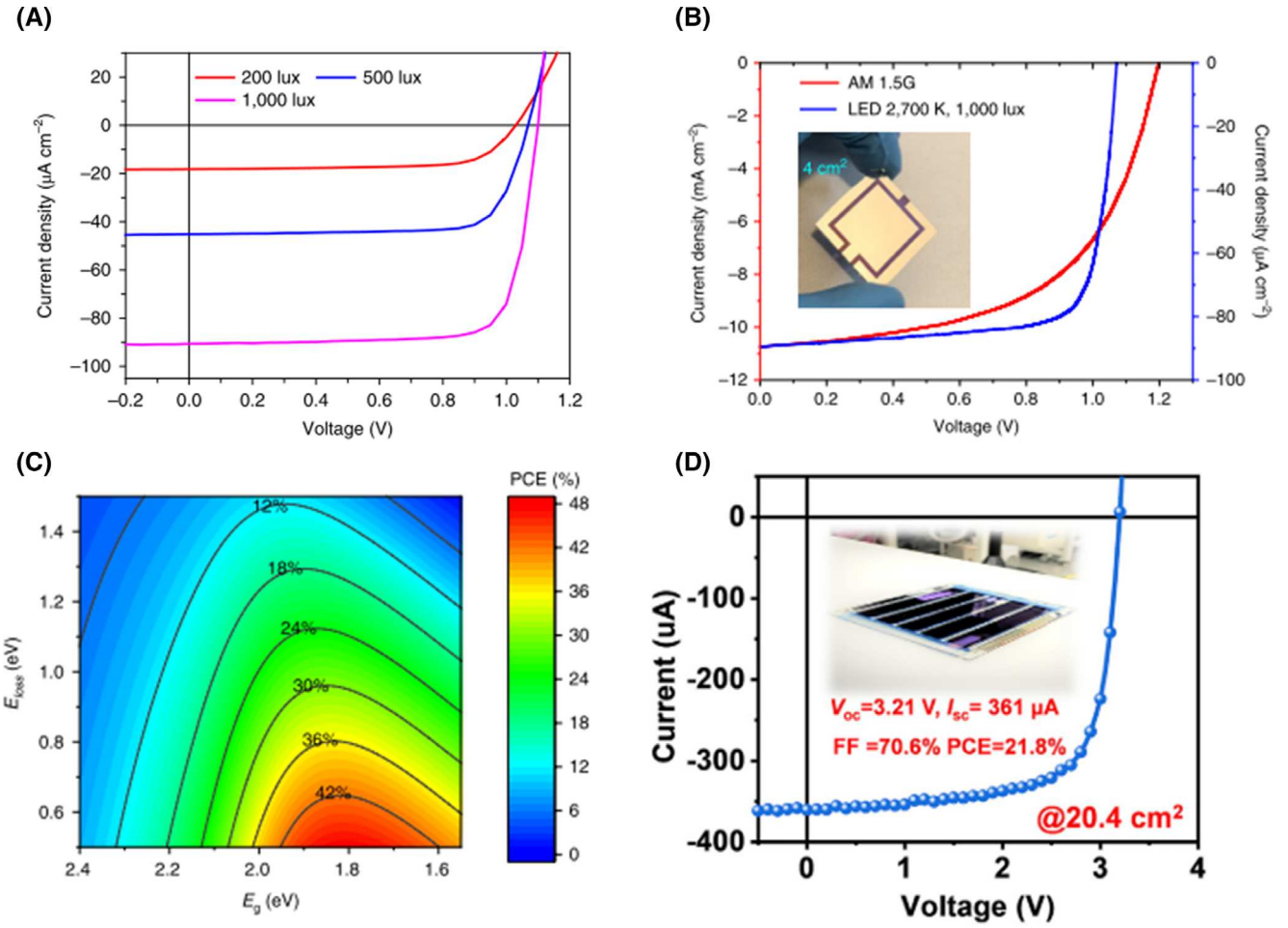

FIGURE 6 (A) *J-V* curves of the PBDB-TF: IO-4Cl-based cell under different indoor light intensities. (B) *J-V* curves of a 4 cm^2 organic solar cells (OSCs) via blade-coating method under AM 1.5 and light-emitting diode (LED) lighting. (C) Efficiency prediction of OSCs under LED lighting condition, with color scale bar indicating power conversion efficiencies (PCEs) of corresponding colors. Copyright 2019, Springer Nature. (D) *J-V* characteristics of TPD-3F-51K: IT-4F module under a fluorescent lamp with a luminance of 1000 lux. Insert is a photo of the OSC module. Copyright 2019, Elsevier

They demonstrated the bandgap of $MA_{0.85}Cs_{0.15}Pb(I_{0.85}Br_{0.15})_3$ can be enlarged to 1.66 eV, which resulted in the highest PCEs of 25.94% and 25.12% under illumination from fluorescent tubes and a white LED.[76] Similarly, Cheng et al. reported a triple-anion $CH_3NH_3PbI_{2-x}BrCl_x$ PSCs with a specially tailored bandgap. As shown in Figure 8(E,F), a record high efficiency of 36.2% was achieved with a distinctive high V_{oc} of 1.028 V.[77] Meanwhile, their large-area cells obtained a PCE of 30.6% and long-term stability, sustaining >95% of the original efficiency under continuous light soaking over 2000 h.

4 | CHALLENGES AND PROSPECTS

In summary, the basic concept and design principles of IPV are introduced. We also provide a summary of the development of Si-based PVs, DSSCs, OSCs, QDSCs, and PSCs under indoor light conditions. Despite exciting progress during past decades, it is still challenging to design high efficiency indoor solar cells and maintain their long-term performance under identical operating conditions. Thus, further improvement is required before commercialization occurs. In particular, IPV optimization is strongly dependent on cell material composition and device designs.

For Si IPVs, intrinsic spectra mismatch and variable performances due to device structure design are still the barriers to better IPV performance. As calculated by Bahrami-Yekta, the optimum thickness of *a*-Si solar cell for indoor applications is supposed to be 1.8 μm.[78] So unlike high absorption coefficient QD and perovskite thin films (few hundred-nanometer thicknesses, for instance), Si cannot yield equivalent efficiency with the same film thickness, which means material purity may become a concern. This results in an inevitable trade-off

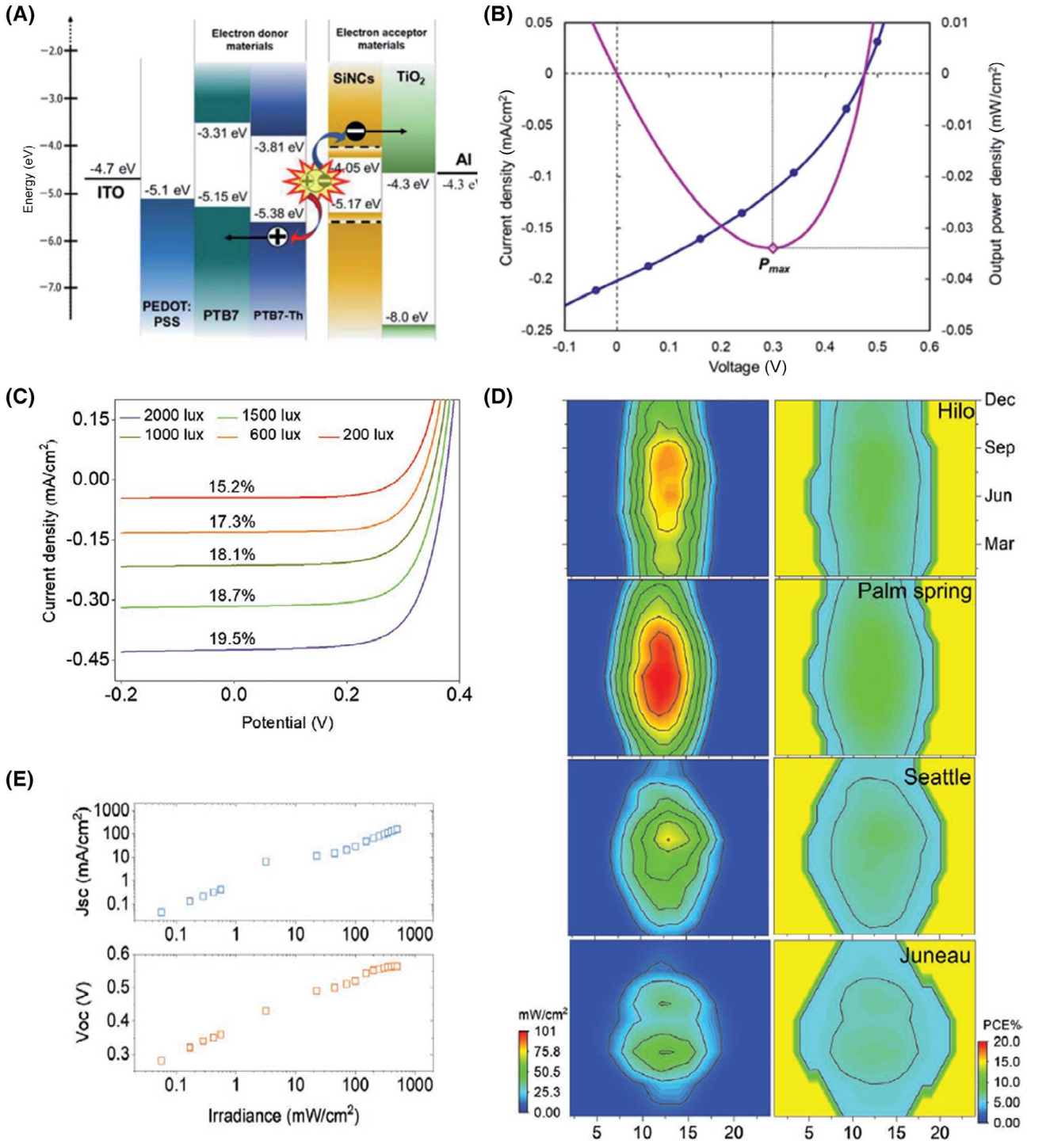

FIGURE 7 (A) Energy diagram of quantum dot (QD)-polymer hybrid PV device. Copyright 2020, The Royal Society of Chemistry. (B) *J-V* characteristics of Si-based QD-polymer hybrid PV device under 1000 lx indoor light. (C) *J-V* curves and power conversion efficiency (PCE) values of QD solar cells (QDSCs) under different indoor light illumination. (D) Left panel shows mean annual daily irradiance of four US cities among different LA and right panel shows simulated mean annual daily QDSC efficiency from selected cities. (E) J_{sc} and V_{oc} dependence on irradiance. Copyright 2020, Wiley-VCH

between device performance and material consumption during the complex device fabrication process.

Compared to Si-based IPVs, DSSCs tend to be more cost-effective and processable. However, the use of costly ruthenium-based dye, the platinum-catalyzed counter electrode, and transparent electrodes remains as concerns for indoor DSSCs.[9,79,80] Liquid electrolytes inside DSSCs can also suffer from the risk of safety and potential

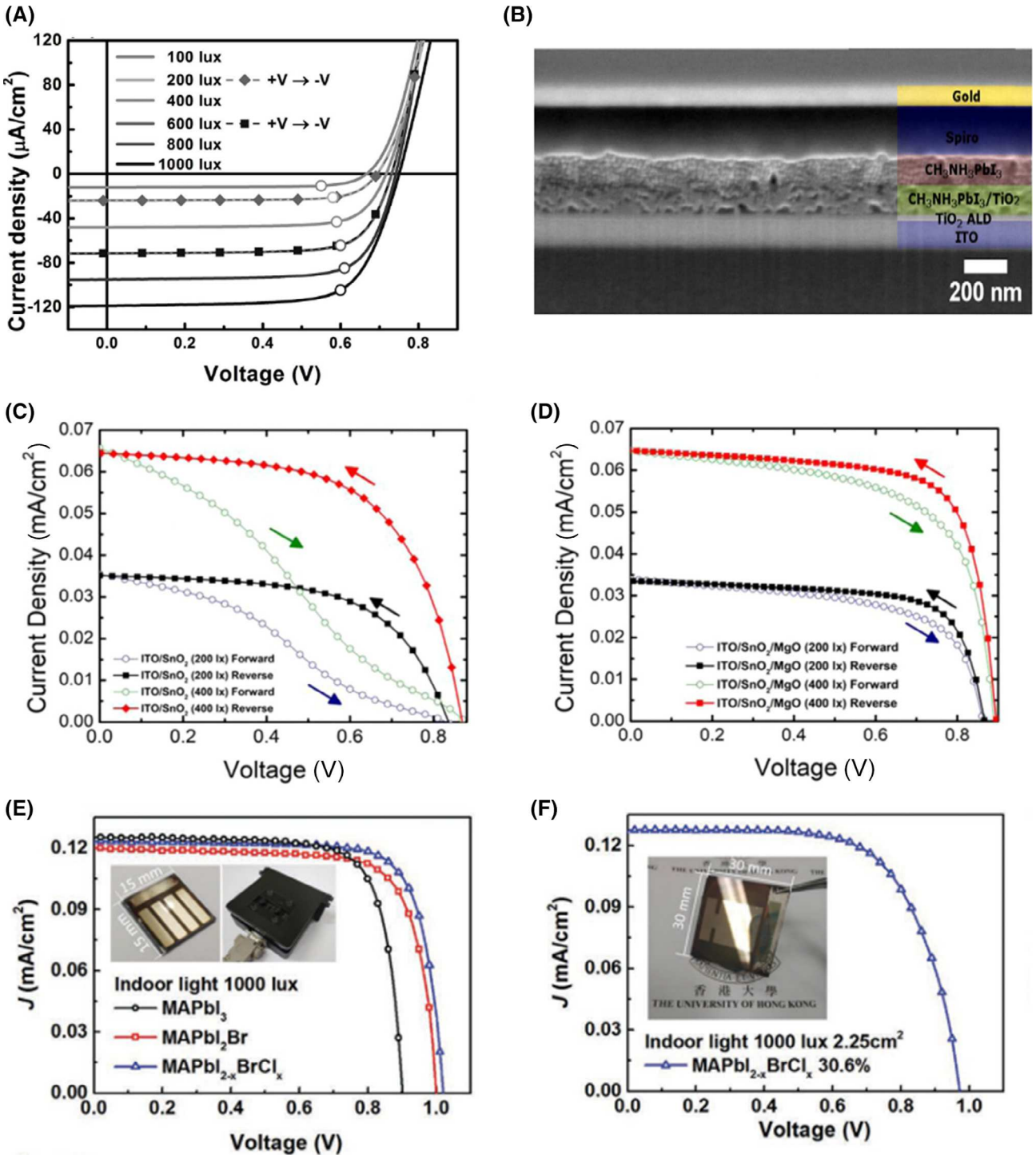

FIGURE 8 (A) *J-V* characteristics of perovskite solar cells (PSCs) with two-step PCBM as an electron transfer layer. The solid lines and dashed lines represent the sweeping direction from negative to positive bias and from positive to negative bias, respectively. Copyright 2015, Wiley-VCH. (B) Cross-sectional SEM image of a Glass/ITO/TiO_2 ALD/TiO_2 mesoUV/ $CH_3NH_3PbI_3$/Spiro-OMeTAD/Au PSC. Copyright 2016, Elsevier. (C) *J-V* curves of ITO/SnO_2 based PSCs under 200 and 400 lx in both forward and reverse bias scanning directions. (D) *J-V* curves of ITO/SnO_2/MgO composite based PSCs under 200 and 400 lx in both forward and reverse bias scanning directions. Copyright 2018, Elsevier. (E) *J-V* curves of the three groups of devices under 1000 lux indoor light (2700 K fluorescent). Inset shows the PSCs (1.5 × 1.5 cm^2) and the test holder for 0.1 cm^2 active area. (F) *J-V* curve of the large area device (3 × 3 cm^2 with an active area of 1.5 × 1.5 cm^2) under 1000 lux indoor light (2700 K fluorescent). Copyright 2019, Wiley-VCH

leakage and degradation. As previously discussed, replacing the liquid electrolyte with a solid-state counterpart is a promising solution to this problem. For instance, in a quasi-solid-state DSSCs, 97% of the initial PCEs can remain after 1000 h test under 200 lux light illumination in an ambient atmosphere.[34]

The limitation for OSCs under indoor illumination lies in the active layer degradation due to sensitivity of moisture, oxygen, and UV light as well as parasitic resistance, which relies on different illumination conditions.[81,82] Also, since fullerene is commonly used as acceptor material in OSCs, thermally induced aggregates and its intrinsic physical energy loss may adversely affect the morphology of active layer, limit V_{oc} and hence performance of OSCs.[83,84] For example, recent research has shown that PCBMs increase sensitivity of OSCs to oxygen and moisture since PCBM will undergo modification upon prolonged oxygen or water exposure, which will severely degrade transport properties inside the PCBM domains and thus impact on the performance of OSCs.[85] Therefore, nonfullerene OSC systems would be a desirable alternative. However, a more in-depth understanding of degradation mechanisms, especially under different low-flux irradiance conditions, is still needed.

To date, there are only a few reports on QDSCs performance in indoor environments, which may be due to relatively lower PCE of QDSCs under standard AM 1.5G outdoor conditions. However, QDs themselves are promising nanoscale zero-dimensional materials which have tunable bandgaps, the discrete density of states, high absorption coefficient, and large-scale processibility. We believe, after the recent seminal work demonstrated by Hou et al.,[13] more exciting results will come in the near future.

PSCs are one of the most promising candidates for IPV application due to their high absorption coefficient, high charge mobility, facile synthesis, and distinctly high defect tolerance. Although Pb-based PSCs have exhibited excellent performance in indoor application, they also feature some shortcomings that should be addressed to enable their long-term stable use. Generally, these limitations are related to the toxicity of heavy metals, high sensitivity to oxygen and water, as well as unsuitable electronic band structure.[9] Toxicity is one of the most significant limitations in PSCs, mainly due to Pb, which is harmful to humans and environment, and this raises the importance of fundamentally addressing the toxicity issues through chemical composition engineering.[86,87] Tin-based perovskites could be able to address toxicity problem, and self-healing encapsulation materials and the incorporation of neutralizers and precipitants such as sulfides may be an effective strategy.[87] Another issue of concern involves instability of perovskite thin films and heightens toxicity concerns as perovskite compounds are unstable due to their sensitivity to moisture, oxygen, heat may result in toxic Pb leakage.[88,89] Since the stability of halide perovskite compounds is mutually related to their toxicity, similar measures mentioned above, such as compositional engineering and advanced encapsulation needs to be explored.[89] Moreover, typical perovskite compounds $MAPbI_3$ exhibit relatively narrow electronic bandgaps around 1.6 eV, which are less favorable for indoor light harvesting. To enlarge the bandgap of halide perovskite approaches such as lattice expansion by incorporating halide double perovskites may be required.

Apart from the abovementioned challenges in each type of IPV, the metrology of IPVs under various indoor radiations has not yet been standardized. Illumination conditions are not uniform as those in the standard AM 1.5G testing condition, including the type of lighting source, intensity, and wavelength. So, the standardization of indoor testing protocols is necessarily required. Under the ambient low light conditions, the device operation mechanisms of indoor thin-film PVs will change. However, to date, research on IPV cell modeling and operation mechanisms are still lacking. Also, there are few studies on long-term stability characterizations under indoor conditions. Nevertheless, considering how much progress has been made in solution-processed solar cells and how many challenges needed to be overcome, there is no doubt that the realization of IPV devices will be *the next big trend* in solution-processed Photovoltaics.

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CONFLICT OF INTEREST

The authors declared no potential conflicts of interest.

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